RETROFEED – Implementation of a Smart RETROfitting Framework in the Process Industry towards its Operation with Variable, Biobased and Circular FEEDstock

Ana González-Espinosa*[1,2]
[1]CIRCE Institute (CIRCE Foundation – University of Zaragoza)
Zaragoza, Spain
e–mail: aigonzalez@fcirce.es

Martina del Cerro, Jorge Barrio, Andrea Hernandez, Diego Redondo
[2]Research Centre for Energy Resources and Consumption (CIRCE)
Zaragoza, Spain
e–mail: mdelcerro@fcirce.es; jbarrio@fcirce.es; ahernandez@fcirce.es; dredondo@fcirce.es

ABSTRACT

Resource and Energy Intensive Industries (REIIs) require large quantities of material and energy inputs to meet the demands of their production processes. The environmental footprint resulting from these operations is therefore substantial and must be reduced to attain more sustainable business practices. RETROFEED is targeted at modifying core process equipment in REIIs to boost energy and material utilisation efficiencies, reduce greenhouse gases (GHG) emissions and replace traditional feedstock with biobased and recycled alternatives. The proposed integration strategy is based on the latest Industry 4.0 assets, including but not limited to development of novel sensors, digitalisation tools and decision support systems that will facilitate the adoption of new practices while maximising performance objectives. Impacts will be evidenced in six demonstration sites in the ceramic, cement, aluminium, steel and agrochemicals sectors. It is expected that by the end of the project, material and energy efficiencies are enhanced by 20%.

KEYWORDS

Industrial Retrofitting; Energy efficiency; Resource reclamation; Circular economy; Biobased; Feedstock; Industry 4.0; Decision Support System

INTRODUCTION

Ensuring a sustainable raw materials supply is at the forefront of the European Union's (EU) strategic policies to meet its economic, climate and energy targets [1]. However, the existing predominance of the manufacturing industry over the extractive industry in the EU leads to a high dependency on the import market [2]. Maintaining industrial competitiveness and economic growth levels high is contingent upon reliable access to these feedstocks, and as a result, several initiatives have been promoted to guarantee a secure supply of these resources [1,3,4]. These actions are based on fostering international partnerships and stakeholder engagement, delineation of regulatory frameworks and boosting availability of "secondary raw materials" sources through the implementation of circular economy and highly efficient utilisation practices [1,2,5]. Nonetheless, definition of strategies to incorporate such methodologies to business-as-usual operations, especially in Resource and Energy Intensive

* Corresponding author

Industries (REIIs), is an ongoing area for development and efforts must still be devoted to enable a climate-neutral, circular economy industrial transformation by 2050 [6]. At the same time, critical and alternative feedstocks are paramount to meet the rapidly increasing energy demands of a growing population and widespread industrialisation while avoiding a concomitant climate crisis [1,7]. EU industries, responsible for 15% of the total emissions, play a key role in the accomplishment of a sustainable production future with minimal environmental footprint [8]. REIIs are particularly relevant in this context, since the high energy intensity of their production processes makes finding substitutes for fossil fuels a complicated endeavour. These limitations manifest how these industries could greatly benefit from retrofitting their processes to gain greater flexibility in their raw material and energy supply sources, shifting towards the use of alternative feedstocks, without compromising efficiency and quality of the production [7].

Advanced digital production (ADP) technologies offer unprecedented benefits in terms of productivity management, raising industrial competitiveness, and can straightforwardly incorporate innovations targeted at reducing the environmental impacts resulting from goods manufacturing [9]. Smart manufacturing practices are making the boundary between physical and digital modifications progressively diffuse, through the integration of cyber-physical systems incorporating artificial intelligence, big data analysis, Internet of Things strategies that may guarantee optimised industrial performance. Among these cyber-physical systems, virtual representations of physical objects, i.e. digital twins, are powerful tools to accelerate decision making in production lines [10]. Higher flexibility in manufacturing environments, also leads to the creation of new market fields, promoting industrialisation and social inclusion [9].

Unfortunately, efforts devoted to the development of ADP technologies are concentrated in a few world economies, as a result of limited capabilities to retrofit existing equipment and integrate digital technologies, knowledge gaps in the development of the latter and financial constraints [9]. On the digital revamping side, the ceramic industry is an example of a sector that has been subject to recent scrutiny to incorporate modelling and data driven approaches to optimise energy and materials consumptions [11,12]. However, while these studies provide a data-driven framework to enhance performance, integration strategies remain unclear. How to overcome difficulties associated to lack of data is also an area for improvement, since industrial settings are not always fully automated.

Retrofitting actions on process equipment lie at the heart of physical modifications aimed at conferring greater resource utilisation flexibility to industries and diminishing their environmental impact. Thus, recent works have proposed novel strategies to boost performance of core equipment in intensive industries, with case studies in the aluminium [13] and steel [14] sectors. Although promising, these are feasibility studies that need further insights into mechanisms for adoption and implementation.

It is therefore evident, that knowledge gaps for the optimisation of material and energy uses in REIIs still exist, and that these industries could prosper should a clear plan of action to incorporate Industry 4.0’s innovations in their processes be delineated. The RETROFEED project intends to facilitate this transition, through application of cutting edge technologies and know-how for the mechanical and digital retrofitting of REIIs, fostering sustainable production practices, circular economy and industrial symbiosis opportunities. The aim of the project is to lean intensive industrial production towards greater feedstock supply flexibility, adopting biobased feedstocks and circular economy principles, to reduce external market dependence and fossil fuel reliance. Mechanical revamping will consist of retrofitting key processes: mainly furnaces and a chemical reactor, and their associated zone of influence, while digital aspects will focus on improving the monitoring and control systems (M&C) through the development of new sensors, digitalisation of core equipment through digital twins, analysis and interpretation of process data and updates in the control loops to reflect the addition of new technologies, where applicable. The Technology Readiness Level (TRL) 7 of RETROFEED's solutions will allow to replicate the technical innovations in other industries in the near future.

Together with the retrofitting of process equipment, Decision Support Systems (DSS) will be tailored to meet each industry's specific requirements, facilitating the transition towards the adoption of new production practices, through assisting plant operators and production managers in determining the best operational conditions to achieve different pre-defined organisational targets considering operational and strategic perspectives. The DSS will be able to forecast production outcomes when considering the new feedstocks availabilities, price and performance, together with other relevant performance indicators, such as emissions generation. To this aim, the DSS will integrate the different developed digital twins of the core equipment, machine learning models to support the optimisation of the processes' performances and additional models to consider the influence zone.

Six industrial sites corresponding to five distinct industrial sectors will demonstrate the effectiveness of the project's strategies to meet the established material and energy goals:

- Torrecid S.A. (TCID) in the ceramic frits sector
- Secil Companhia Geral de Cal e Cimento, S.A. (SECIL) in the cement sector
- ASAS Aluminyum Sanayi Ve Ticaret Anonim Sirketi (ASAS) in the aluminium sector
- Ferriere Nord S.p.A. (FENO) and Tenaris Silcotub S.A. (SILCOTUB) in the steel sector
- Fertiberia S.A. (FTIB) in the agrochemicals sector

Activities in the REII sites will be supported by five Research and Technological Development Centres (RTDs):

- Centro de Investigación de Recursos y Consumos Energéticos (CIRCE)
- Asociación de Investigación Metalúrgica del Noroeste (AIMEN)
- Instytut Energetyki (IEN)
- RINA Consulting – Centro Sviluppo Materiali S,p.A. (CSM)
- IVL Svenska Miljöinstitutet AB (IVL)

Two specialised engineering firms:

- HTT Engineering Spol SRO (HTT)
- Sistem Teknik Endustriyel Firinlarlimited Sirketi (STEK)

Three environmental and energy consulting firms:

- Energy Efficiency in Industrial Processes ASBL (EEIP)
- RINA Consulting S.p.A (RINA-C)
- Geonardo Environmental Technologies Ltd (GEO)

And two Information Technology (IT) firms:

- ODYS S.r.l. (ODYS)
- OPTIT S.r.l. (OPTIT)

METHODS

The RETROFEED project was conceived through interdisciplinary collaboration between project partners, who determined what actions were adequate to meet the demands of each industrial sector and proposed a methodology to execute them. Modifications to be performed on core equipment and strategies for successful integration were agreed upon, and this know-how consolidated into the project's description of action. Overall, RETROFEED is structured to address three main focus areas for attainment of the proposed objectives:

- ✓ Process characterisation and revamping/development of process equipment
- ✓ Development of sensors and digitalisation tools to boost performance and facilitate integration of the proposed feedstock changes
- ✓ IT integration of full plant operation consolidated in decision support systems

At the same time, RETROFEED solutions mark a breakthrough in the operation of REIIs not only due to the novelty of the proposed process modifications, but also because of their replicability and synergistic potential. Technological developments can be easily transferred to other industries belonging to the same sectors as RETROFEED partners, but most notably, across the various industrial sectors involved in the project. Moreover, synergies between the processes have been established, detecting opportunities to exploit industrial symbiosis relationships further. Therefore, after thorough characterisation of the processes occurring in each REII, a synergies and complementarities analysis was performed, evidencing the full potential of the proposed changes.

Under the stated project framework, objectives pursued by each industrial sector were clearly identified and a plan of action delineated. Quantification of measurable impacts of the proposed changes will be possible in the project through a consensual definition of performance indicators between project partners. However, at this stage in the project's development it is possible to provide a series of qualitative effects alongside preliminary metrics that will unequivocally be realised. Following is a description of the main drivers that led industrial partners to participate in the project, together with proposed solutions to guarantee successful fulfilment of those goals.

TCID will lead activities in the ceramic sector where retrofitting actions will be focused on the frits furnace. A smart combustion control of the smelter will be implemented, achieving an automatic adjustment of the combustion conditions to the requirements of each frit recipe. To aid in this purpose, a weighing system for the raw material feed input to and output from the furnace will be integrated in the monitoring system. This new approach will allow to reduce the time between load changes, promoting the reduction of raw material losses during these transitions. In addition, a redesign of the flue gases heat recovery system will be tested pursuing a dual purpose: optimizing the pre-heating of the combustion air stream and extending the use of the hot air for the frits drying process. These efforts altogether, lead to increase the energy and resource efficiencies of the plant's core process.

Modifications at SECIL's cement manufacturing facilities will be concentrated around its core equipment: the rotary kiln. In this case, a full-scale multi-fuel burner that can be powered with alternative fuels will be designed and installed in place of the main burner of the kiln. The development of new sensors such as 1) Image-based combustion diagnosis tool 2) Alternative fuels properties determination and 3) Real-time optical characterisation of clinker composition will allow to monitor and control combustion conditions and clinker quality subsequently, and will provide additional support to optimise the kiln performance. In addition, a flue gases analyser will be integrated in the M&C system.

ASAS pursued objective is to increase the amount of scrap that can be fed to the aluminium melting furnace. For this purpose, a delacquering system, capable of removing most of the scrap's surface contamination, will be installed at the raw materials feeding line, allowing to increase the share of highly contaminated scrap to be used in the aluminium smelting process. At the same time, an oxygen (O_2) injection system and burner head will be designed and installed in the furnace to increase combustion efficiency and fully oxidise combustion products. To ensure adequate operation and emissions generation conditions, both an O_2 sensor and Total Organic Carbon (TOC) analyser will be incorporated in the furnace's control system.

In the steel sector, two different end-users are involved: FENO and SILCOTUB. In both cases, activities will focus on the Electrical Arc Furnaces (EAFs) to apply circular economy concepts. While FENO's strategy implies using plastic grains and biochar as natural gas substitutes in a burner, SILCOTUB's plan is to inject plastics and rubber into the furnace to release energy to the melt. At the same time, FENO will attempt to reduce anthracite feeding to the furnace by using biochar as a carbon source instead, whereas SILCOTUB intends to employ sludges and dust as raw material replacements. In both cases the M&C system will integrate these solutions and new sensors to enhance the EAFs performances.

Finally, FTIB denoting the agrochemicals sector, will attempt to reduce the external reliance on phosphorous based reactants, through substitution of energy yielding reactions and fostering industrial symbiosis opportunities. Phosphorous material imports will be cut back through the design of new equipment able to react alternate chemicals, and through the incorporation of biobased wastes such as ashes from food production facilities. Additionally, by-products from neighbouring industries will be reacted with their local counterparts to obtain raw materials for fertiliser production. The M&C system will be improved to consider the new feedstock and energy provision approaches.

PRELIMINARY RESULTS AND FUTURE OUTLOOK

As mentioned, a set of performance indicators will be defined and their values assigned throughout the project, prior to and after the retrofitting. Some preliminary estimations have been made, and the results together with generic performance attributes of the proposed solutions are presented next.

In the case of TCID, the retrofitting actions will increase the energy and material savings through optimisation of fuel usage and air thermal conditions for combustion and drying, and regulation of water flows. Moreover, a 4 to 6-fold reduction of material waste during the time between load changes will be achieved, leading to an increment in the furnace's productivity. The optimisation of combustion performance, through modelling and enhancement of the monitoring and control system, together with the integration of a new drying frits strategy will decrease the emissions generation during frits manufacturing.

The retrofitting solutions to be implemented in SECIL will promote the reduction of carbon dioxide (CO_2) emissions through fossil fuel switching for biobased counterparts, attempting to substitute between 60 – 80% of the thermal energy required for calcination. At the same time, through a greater degree of control over the kiln's thermal conditions, a reduction of at least 5% of the specific energy consumption (kcal/kg clinker) is expected. Moreover, the new strategies will lead to an increment of the energy efficiency without altering the product quality and productivity. The improvement of the monitoring and control system will allow a faster response over the system when variable feedstock is introduced, optimizing clinker production.

In ASAS, the share of scraps to be used for smelting is expected to experience roughly a 50% increase, reducing primary aluminium consumption. This substitution together with the modifications concerning the delacquering unit, may significantly affect the energy toll of the process: the new conditions require about 15 times less energy than current practices. In addition, the new O_2 injector together with the new sensors to be installed will ensure more efficient combustion and emissions generation conditions to maintain product quality and exert greater control over the exhaust gas composition.

The retrofitting actions in FENO will lead to reduce the GHG emissions because more sustainable feedstock will be incorporated, integrating circular economy concepts and biobased sources. As a result, the fossil fuel dependence will decline during the steel production, in an amount that will be determined through experimentation. The degree of substitution of the traditional feedstocks will be the maximum admissible by the process without altering productivity or product quality. Similarly, the main results expected in SILCOTUB are related to raw materials reclamation from wastes containing lime, carbon and iron. This way, the landfilling residues and costs will be minimised, together with capital expenses associated to feedstock purchasing.

FTIB will gain greater raw material supply flexibility after the retrofitting, which will confer higher feedstock autonomy. Besides, this approach will lead to a reduction in indirect and direct costs: modifications will attempt to substitute at least 10% of the currently employed phosphorous sources, simultaneously cutting back on costs since prices of the alternative feedstocks are estimated at roughly half the value corresponding to their conventional counterparts. Phosphorous recovery is also in line with the EU's objectives under the Action Plan on Circular Economy, to secure reliable access to Critical Raw Materials (CRMs) [2]. Energy resources will also be positively affected through the process retrofitting, since the heat generating reaction to be incorporated in the fertiliser production line, has an energy yield 3 times greater than the currently employed pathway. New sensors will be implemented in the M&C system to accomplish an improved performance of the plant under the new conditions and avoid negatively influencing the amount of rejected product.

RETROFEED is aimed at providing industries with strategies and engineering tools to help them meet their sustainability goals. A preliminary estimation of the impacts of the retrofitting activities presented in this report has been made resulting in about 20% increases in resource and energy utilisation efficiencies, and average reductions GHGs and fossil-based sources reliance of 30% and 20% respectively, resulting in mean operating expenses savings of 30% and likewise, mean productivity increases of 20%.

Synergies & complementarities

Substitution of traditionally used feedstock represents a great challenge for industries, since RETROFEED changes should under no circumstance compromise productivity or product quality. Under the latter premise, it was possible to detect similarities between the constraints to which the feasibility of proposed alterations was subject to, revealing that RETROFEED solutions designed for a specific industry, may actually be applicable to other sectors. To accommodate for the mechanical revamping of the core equipment, RETROFEED must address concerns that can be classified into three main categories: alternative raw materials prerequisites, energy yield of the alternative feedstock and final product quality. Given that these aspects are of common interest to all industrial partners, after their careful assessment, replication opportunities across the involved sectors were identified.

One of the main obstacles in replacing fossil fuels in energy demanding processes, is to obtain replacements with similar calorific values. Additionally, the moisture content of biobased alternatives tends to represent an operational hindrance that discredits large-scale implementation of these fuels. Through the development of a novel sensor, SECIL plans to incorporate in its fuel dosing line, a device to estimate the lower heating value of the alternative materials. Both FENO and SILCOTUB depend greatly on achieving adequate thermal and chemical conditions inside their furnaces and thus rely heavily on the combustion performance of their fuels. Incorporating a sensor such as SECIL's in the process lines, would increase their autonomy in terms of feedstock selection and guarantee safe operating conditions, without endangering the continuity of the steel production operations.

Another novelty to be integrated into SECIL's clinker production line is a sensor to verify the crystallographic structure of the produced clinker, ensuring quality of the product, significantly cutting back times of sampling and chemical analysis. Since TCID's ceramic frits share the same chemical nature (covalent bond structures), this sensor could potentially be tailored and adapted to determine the frits composition.

ASAS and TCID both depend on achieving flame stability, shape and temperature conditions in their furnaces, making the adoption of the flame visualisation tool for combustion diagnosis to be developed at SECIL directly transferrable. At the same time, the cement company plans to design a multi-fuel burner, capable of processing fuels other than fossil based; an alternative that could also be explored in the aluminium and ceramic sectors. Advancements on the burner designed for FENO could also be leveraged upon to facilitate adaptation of the multi-fuel burner to each specific use case.

SILCOTUB plans to recover valuable compounds from the EAF dust to use as raw materials for steel production. On the other end, SECIL already uses flue dust in another facility within the firm. These opportunities are particularly relevant to industries such as ASAS and TCID where metal dusts are formed as a result of the smelting processes and could potentially be valorised as a means of raw materials reclamation.

Both FENO and SILCOTUB may potentially benefit from the delacquering and emissions control system to be installed at ASAS, should a higher degree of scrap cleaning be deemed beneficial to boost production yields and curtail pollutants quantities in the off-gases. This option, however, requires careful examination of the associated trade-offs and tangible benefits.

Lastly, a significant amount of RETROFEED activities involve energy generation through chemical reactions. FTIB will incorporate in the fertiliser production process a reaction that can supply three times as much energy as the currently employed pathway, which although not directly transferrable to other sectors, evidences the flexibility potential of chemical reactions that may be tailored to meet the specific demands of the end users.

Industrial symbiosis and circular economy concepts are closely related. The former basically implies detecting opportunities where industries may benefit from valorising by-products or wastes produced by other facilities, while the latter consists on minimising material entries and exits, bolstering utilisation efficiency. For industrial symbiosis to be feasible, industries should ideally be strategically located, to augment the profitability of the exchange. Although proximity is not a distinctive feature of RETROFEED's participating industries, a careful economic and environmental assessment should be carried out to determine whether they may leverage upon these findings. Nonetheless, potential relationships presented represent a guideline for the involved sectors to increase awareness on how they may boost the efforts dedicated to the establishment of a circular economy. Summarised below are different alternatives that may be explored further:

- Recovery of industrial grade lime from TCID's wastewaters to be used in virtually all other production processes.
- Lixiviation of EAF dust using wastewaters generated from steel polishing, to separate heavy metals and recover valuable species for plant growth such as zinc, iron, and manganese.
- Valorisation of ASAS slag containing aluminium and aluminium oxide, as raw material for TCID, slag forming agent in FENO and SILCOTUB's EAFs and steel killing (removal of excess oxygen). At the same time, the oxide may be turned into salts FTIB employs in the fertiliser production process, such as aluminium sulphate.
- Utilisation of waste frit produced at TCID as raw material for the steel sector, due to its high refractories content, typically consisting of silicon, magnesium, aluminium, among others. Likewise, the slag produced at the steel production facilities, may serve as a raw material for the ceramic frits process, given its high content in aluminium and other metal oxides employed in frit production.

CONCLUSION

This document summarises the retrofitting actions to be carried out in six different demonstration sites to be able to shift current production practices towards introducing variable, biobased and circular feedstock and the pathways devised for successful accomplishment of such goal. It also presents the potential synergies and replication opportunities that may arise between the different sectors as a result of the activities within this project.

The project RETROFEED is intended to tackle the demanding feedstock market for the REIIs making them more adaptable to the new production scenario where the use of material and energy resources should be optimised. For RETROFEED's purpose, the activities are focused on core equipment, namely furnaces and chemical reactor, where mechanical retrofitting actions will be implemented and digital solutions developed, such as digital twins. Additionally, a DSS will integrate the different models to support the decision-making process from operational and strategic perspectives.

The universality of RETROFEED solutions was evidenced through the identification of synergies and replication opportunities across all involved sectors. Trade-off and viability analyses are required however, to determine the breakeven points where these operation pathways leverage on the benefits of a circular economy as opposed to incurring in excessive material and energy uses and associated emissions to enable their adoption.

Overall, it is expected that by the end of the project, RETROFEED will have developed a series of disruptive methodologies that facilitate the EU industries' transition towards more sustainable and responsible production practices.

ACKNOWLEDGMENT

This work was performed in the framework of the RETROFEED project (Implementation of a Smart RETROfitting Framework in the Process Industry towards its Operation with Variable, Biobased and Circular FEEDstock). This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.869939

Authors would like to thank the industrial partners for their fruitful collaboration.

NOMENCLATURE

Acronyms/abbreviations

ADP – Advanced Digital Production
AIMEN – Asociación de Investigación Metalúrgica del Noroeste
ASAS – ASAS Aluminyum Sanayi Ve Ticaret Anonim Sirketi
CIRCE – Centro de Investigación de Recursos y Consumos Energéticos
CRM – Critical Raw Material
CSM – RINA Consulting – Centro Sviluppo Materiali S,p.A.
CO_2 – Carbon dioxideDSS – Decision Support System
DSS – Decision Support System
EU – European Union
EAF – Electrical Arc Furnace
EEIP – Energy Efficiency in Industrial Processes ASBL
FENO – Ferriere Nord S.p.A.
FTIB – Fertiberia S.A.
GEO – Geonardo Environmental Technologies Ltd
GHG – Greenhouse Gases
HTT – HTT Engineering Spol SRO
IEN – Instytut Energetyki
IT – Information Technology
IVL – IVL Svenska Miljöinstitutet AB
M&C – Monitoring & Control
O_2 – Oxygen
ODYS – ODYS S.r.l. (ODYS)
OPTIT – OPTIT S.r.l. (OPTIT)
REII – Resource and Energy Intensive Industry
RINA-C – RINA Consulting S.p.A
RTD – Research and Technological Development Centres
SECIL – Secil Companhia Geral de Cal e Cimento
SILCOTUB – Tenaris Silcotub S.A.
STEK – Sistem Teknik Endustriyel Firinlarlimited Sirketi
TCID – Torrecid S.A
TOC – Total Organic Carbon
TRL – Technology Readiness Level

REFERENCES

1. European Commission "Policy and strategy for raw materials | Internal Market, Industry, Entrepreneurship and SMEs," 2020. https://ec.europa.eu/growth/sectors/raw-materials/policy-strategy_en [Accessed: 6-August-2020]

2. European Commission "Report on Critical Raw Materials and the Circular Economy". https://op.europa.eu/en/publication-detail/-/publication/d1be1b43-e18f-11e8-b690-01aa75ed71a1/language-en/format-PDF/source-80004733 [Accessed: 7-August-2020]
3. Industrial Mineral Europe, "Raw Materials Initiative". https://www.ima-europe.eu/content/raw-materials-initiative%20 [Accessed: 10-August-2020]
4. European Commission "Communication from the Commission to the European Parliament, the council, the European economic and social committee and the committee of the regions" https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0021&from=EN [Accessed: 6-August-2020]
5. European Commission "Recovery of critical and other raw materials from mining waste and landfills" https://publications.jrc.ec.europa.eu/repository/bitstream/JRC116131/aaa_20190506-d3-jrc-science-for-policy-recovery_of_rm_from_mining_waste_and_landfills_4_07_19_online_final.pdf [Accessed: 10-August-2020]
6. European Commission, "Industry". https://ec.europa.eu/growth/industry_en [Accessed: 6-August-2020]
7. "EUROPE 2020 A strategy for smart, sustainable and inclusive growth." https://ec.europa.eu/eu2020/pdf/COMPLET EN BARROSO 007 - Europe 2020 - EN version.pdf [Accessed: 6-August-2020]
8. European commission, "Industrial Market Entrepreneurship and SMEs". https://ec.europa.eu/growth/industry/policy/energy-intensive-industries_en#:~:text=Energy%2Dintensive%20industries%20(EIIs),transport%2C%20construction%20and%20power%20generation [Accessed: 6-August-2020]
9. United Nations Industrial Development Organisation (UNIDO) "Industrial Development Report 2020. Industrializing in the digital age. Overview". https://www.unido.org/sites/default/files/files/2019-11/UNIDO_IDR2020-English_overview.pdf [Accessed: 4-August-2020]
10. Qi, Q., and Tao, F. Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison. Ieee Access, 6, pp 3585-3593, 2018.
11. Ma, S., Zhang, Y., Yang, H., Lv, J., Rend, S. and Liuef, Y. Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries. Journal of Cleaner Production, on-line version, 2020.
12. Ma, S., Zhang, Y., Lv, J., Yang, H., and Wu, J. Energy-cyber-physical system enabled management for energy-intensive manufacturing industries. Journal of Cleaner Production, 226, pp 892-903, 2019.
13. Royo, P., Ferreira, V. J., López-Sabirón, A. M., García-Armingol, T., and Ferreira, G. Retrofitting strategies for improving the energy and environmental efficiency in industrial furnaces: A case study in the aluminium sector. Renewable and Sustainable Energy Reviews, 82, pp 1813-1822, 2018.
14. Dal Magro, F., Jimenez-Arreola, M., and Romagnoli, A. Improving energy recovery efficiency by retrofitting a PCM-based technology to an ORC system operating under thermal power fluctuations. Applied Energy, 208, pp 972-985, 2017.